Optimisation of District Heating & Cooling systems

D5.2: Optimisation and control algorithms specification

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Optimization and control algorithms specification

The developed tools are built around three main categories that are addressed in T5.2, the control configuration selection and the application in the DHC systems and the structuring of the control, the Optimization based control and the model predictive control, and the new thinking about the DHC system based on the service oriented architecture.

In this deliverable, the conceptual description of the different tools and architectures at different levels of the DHC are presented.

Keywords: Model predictive control, consumer comfort, control configuration selection, automatic synthesis, machine learning, Service Oriented Architecture, Optimisation based control.

Abstract (public):
Work package 5 of the OPTi project deals with the development of control and Optimisation methods for DHC systems. The developed tools are built around three main categories that are addressed in T5.2, the control configuration selection and the application in the DHC systems and the structuring of the control, the Optimization based control and the model predictive control, and the new thinking about the DHC system based on the service oriented architecture.

In this deliverable, the conceptual description of the different tools and architectures at different levels of the DHC are presented.

Keywords: Model predictive control, consumer comfort, control configuration selection, automatic synthesis, machine learning, Service Oriented Architecture, Optimisation based control.
EXECUTIVE SUMMARY

This deliverable provides the conceptual description of the optimisation and control algorithm that are developed and executed under task 5.2 in the OPTi project. This document focuses on the methodologies that are developed during the work package and the description of the tools that already presented in the deliverable D5.1. The work is classified mainly, as noted in the description of T5.2, into three main categories: the control configuration selection and the control system structuring and its application in DHC system, the optimization based control with different approaches and at various levels and finally the service oriented architecture.

The control structure is a key factor that has a significant impact on the overall plant. The control configuration structure is the first step to ensure a stable, efficient and fast response of the controlled plant. The selection of the correct pairing between important points to be controlled in the plant and the right actuation points is the result of these steps. In addition to that, the right structuring of the control system will help to improve the overall performance of the system. The diagnosis of the correct loops and the correct cascading of distinct stages will achieve the required optimality of the plant.

Optimization based control started to get more attention in the last decade in the DHC systems. The classic DHC system control structure has its source from a knowledge based control approach that is based on a knowledge operator or static offline optimizers. In this deliverable, the optimization based control is presented as a key tool to efficiently operate the DHC networks. The model predictive control and the seeking control were introduced at various stages in the plants with different application scenarios.

The evolution of Service Oriented Architecture encourages the application in DHC plant. The concept was discussed and introduced to the DHC systems. The flexibility of the concept improves the performance of the DHC system and provides a new understanding for the structuring of the control system.
OPTi

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1 INTRODUCTION

The OPTi project develops and combines beyond state-of-the-art technologies and solutions for DHC systems that will improve the operation of the DHC networks. The new developments in automatic control theory, the computing, communications and simulation tools and the measurements and actuations equipment make it possible to optimize the plants and to provide an automatic plant wide control that will achieve the required objectives. Nowadays, it is possible to provide flexible automatic tools that are capable of optimizing the plant according to different operational objectives.

This deliverable provides a conceptual description and explanation of the algorithm, tool prototypes and control methodologies that enable a systematic and optimal way of designing and updating the strategies for the optimal and efficient operation and control for DHC systems. The description and explanation will include but not limited to:

- optimal selection of the control structure and the hierarchy of the control system
- different optimization tools at different level in the DHC system
- service oriented architecture that enables the flexible operation of various parts in the DHC network.

1.1 BACKGROUND AND MOTIVATION

The aim of the OPTi-Framework is to provide a set of tools for control and optimisation that the engineers at DHC plants can use to improve the efficiency of their plant. These tools will therefore target the engineering of the systems as well as how their operation can be optimised.

DHC plants as complex and large-scale systems are challenging from a control and optimisation perspective. The geographical distribution of the network, production units and consumers, in combination with the transportation of the heating/cooling medium create limitations in performance and possibilities to actuate the system. Moreover, control approaches for optimal performance and robustness render highly complex control and optimisation solutions which are difficult to engineer and maintain and are often vulnerable to local failures. The OPTi-Framework targets methodologies which consider this complexity and potential trade-offs and aid the DHC engineer in a systematic design.

The outset of the tool development were the requirements, use-cases and the architecture from the OPTi deliverables D2.1 and D2.5 while keeping the applicability to a general DHC system in mind.

The different tools therefore address different scopes. The scope can be high level (e.g. production levels, user comfort), low-level (e.g. operation of substations, control of pumps and valves) or somewhere in between.

1.2 DHC NETWORK

Like a standard energy network, the DHC network of Luleå city consists of three main parts: The generation, the transportation and the end users. Since the city is the city is geographically large, many generation units are distributed over the city. Figure 1 shows the DHC network. The main generation unit uses a combined heat power (CHP) plant that is located near the steel factory and utilizes the waste hot gas generated from the steel plant as its primary energy source. The power/heat generation ratio is determined based on the demand and the electricity price market. In addition to the CHP, four other power units are geographically distributed over the city, except HVC2 which is located near the CHP plant.
The distribution network consists of large network of pipes (2 x 22376 pipes - supply and return) that deliver the heat energy to most parts Luleå City. Pumping stations will ensure optimal flow in the network such that an optimal energy transfer to all the consumers in the city is guaranteed. In each power generation unit is a pumping station. In addition to that, three additional pumping stations help to boost the energy transfer (TSP1-TSP3). The third part are the 9533 consumers with variable different loads and consumption profiles. More details about the DHC network and its modelling are given in D4.3.

1.3 CURRENT CONTROL AND OPTIMISATION APPROACHES

The main current control methodology at Luleå DHC can be categorized into two levels: the low level, which consists of controlling the pumps to provide sufficient differential pressure at different nodes in the DHC plant and a high level, which controls the power plant generation operations. The low level is done in a fully automated manner through the adoption of Proportional Integral Differential (PID) controllers that actuate (adjust) the speed of the pumps in order to achieve a certain differential pressure at specific weak points in the grid.

Each pump controls a section in the network by keeping the pressure above or equal to a certain level (set-point). In each section, one or more points are identified as weak points. At these weak points, the differential pressure should not go below a certain level, otherwise the connected branches will be affected. The controller will take the minimum value of these weak points and will keep the lowest equals to the desired level. The pressure level set-points of the controllers are kept constant during the entire operation of the DHC plant.
Table 1 shows the pumping stations and related differential pressure (DP) points.

**Table 1: Pumping stations and related DP points**

<table>
<thead>
<tr>
<th>Pumping Station</th>
<th>Pressure Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHP (KVV)</td>
<td>Lulsundet</td>
</tr>
<tr>
<td>HVC1</td>
<td>Öhemmanet</td>
</tr>
<tr>
<td>HVC2</td>
<td>Lulsundet</td>
</tr>
<tr>
<td></td>
<td>Tuna</td>
</tr>
<tr>
<td>HVC4</td>
<td>Trollnäs</td>
</tr>
<tr>
<td>HVC5</td>
<td>Folkhögskolan</td>
</tr>
<tr>
<td></td>
<td>Kyrkbyn</td>
</tr>
<tr>
<td>TSP1</td>
<td>Bergnässkolan</td>
</tr>
<tr>
<td></td>
<td>Trollnäs</td>
</tr>
<tr>
<td>TSP2</td>
<td>F21</td>
</tr>
<tr>
<td>TSP3*</td>
<td>Öhemmanet</td>
</tr>
</tbody>
</table>

*TSP3 act as a slave unit for HVC1. The TSP3 speed is equal to a percentage of HVC1 speed.

The pumping stations are started manually, but the operation contains some protection procedure to prevent the pressure to go higher than a certain limit before and after the pumps. For example, the main pumping station at the CHP plant (KVV) has two pumps as it can be seen in Figure 2. The protection control will keep the pressure before the return pump above 4 bar and before the supply pump above 5 bar, while the pressure after the supply pump should be kept below 15 bar. The logic will interact to change the speed set point and overtake the main DP controller.

In addition to the DP control mode, the controller can operate in several stations in flow control mode. However, this mode is limited to start-up sequences. Additional protection is activated when working in flow mode to ensure that the differential pressure at the related weak point(s) stays within certain limits.
Figure 2: Schematic modelling diagram of CHP (KVV) and HVC2 Power and pumping stations

Power control is responsible for the operation of the overall network. As the pump control is acting as secondary stage to the power control, it can be classified as the highest level. Therefore, the DP control can be seen as the fast system that will maintain the DP (and the flow as a consequence) to be optimal. While the power control, which is the slow system, will ensure that the temperature in the network (and accordingly the delivered power to the consumers) is optimal. The power is mainly controlled in the main CHP (and in some summer occasion through HVC2 which is located in the same area of the KVV) to ensure that the supply temperature at the station is following a certain curve related to the outdoor temperature. Figure 3 shows the current operational curve for Luleå DHC.
The power generation units are geographically distributed over Luleå, as stated earlier. These units have some features to that prioritise the starting and stopping of each unit. Table 2 shows the key features of the power generation unit and their start-up sequence.

Table 2: Generation Power Plant

<table>
<thead>
<tr>
<th></th>
<th>HVC1</th>
<th>HVC2</th>
<th>HVC4</th>
<th>HVC5</th>
<th>CHP (KVV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power (MW)</strong></td>
<td>Oil:3, Tot=60 Elect=2, Total=80</td>
<td>Oil and gas: 2. Tot=160</td>
<td>Wood Powder &amp; Oil. Tot=25</td>
<td>Oil, 2. Tot=24.9</td>
<td>Gas Turbine. Gas and Oil Tot=185</td>
</tr>
<tr>
<td><strong>Limitation</strong></td>
<td>&gt;30% of Max P</td>
<td>&gt; 15 MW per boiler</td>
<td>&gt; 8 MW</td>
<td>&gt;30% of Max P</td>
<td>Generation can be balanced during high electricity prices. Slow start up time</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>~88 % oil ~99 % Electricity</td>
<td>~80-90%</td>
<td>~92% oil ~93 % powder</td>
<td>~90%</td>
<td>~75% on yearly ~90 % Winter</td>
</tr>
<tr>
<td><strong>Start Time</strong></td>
<td>~ 20 min</td>
<td>~ 20 min</td>
<td>~ 30 min</td>
<td>~ 20 min</td>
<td>Hours</td>
</tr>
<tr>
<td><strong>Start Sequence</strong></td>
<td>3</td>
<td>5/4</td>
<td>2</td>
<td>4/5</td>
<td>1</td>
</tr>
</tbody>
</table>

1.4 DOCUMENT ORGANISATION

The deliverable starts with an introduction about the three levels approach that is adopted in structuring the control tools in this project. Then, the control configuration selection tools that provides the best understanding about the interactions between various parts in the network is presented. The automatic
tuning tools that will improve the performance of the building substations is presented. The optimization based control represented by the model predictive control and the seeking control will be presented in the next two sections with the applicability in DHC networks. The service oriented architecture is discussed and the conclusion is presented in the concluding section. Note that the state of the art is distributed over the sections with the findings and publications that resulted from this project.
2 OPTi - CONTROL AND OPTIMISATION APPROACH

As noted in the deliverable D5.1, in OPTi the hierarchy of the optimisation and control approach makes use of three layers which are depicted in Figure 4:

- **Low-level control (LLC)** of pumps, valves and production units. This includes control configuration selection and design of controllers.
- **Optimisation based control (OBC)** of the DHC system by adjusting set points for the low-level control. This includes the consideration of forecast information.
- **Optimisation of operation (O3)** considering (A) DR strategies and production scheduling.

![Figure 4: Schematic of the applied control and Optimisation hierarchy.](image)

It has to be noted that the purpose of the hierarchy is only used from a logical perspective. Nevertheless, centralized optimisation schemes which make use of various information from within the DHC system, will operate as one hierarchical layer. In the sequel, the different tools will be associated with these three layers.

2.1 LOW-LEVEL CONTROL

The low-level control provides the first step that will enable the high-level controllers to control certain devices with less complexity. The low-level control can be identified by two main schemes, local and fast. The local scheme means that the controller will consider the effect of a certain action on a certain local location which does not necessarily be geographically close to the action point. While the fast scheme is meant to be fast compared to the higher level. The controller will act in a fast way such that the lower system will not appear to have any dynamics compared to the upper level time scale.

The Low-level control does not necessarily need to be in one single stage. For example, consider the flow control that uses a control valve to achieve the required flow. The flow controller is a low-level control that uses a single point controller (ex. PID controller) that measures the actual flow. Then, to achieve the requested reference flow, the valve positions is adjusted, representing an actuated signal. To accomplish this, a lower control loop exists that will receive the actuation signal (the valve position) as a set point, then control a servo motor to adjust the valve position to achieve the requested position. From the flow control point of view, the valve position is a low level control but from the plant optimiser level (that sets the optimum flow that will achieve the optimal operational state) the flow control is a low level also.
2.2 Optimisation-Based Control

This is the middle layer in the control structure. It works on optimising a specific operation of the plant. It is used usually to optimise certain objectives and mostly a single objective. The controller is a mid-range plant wide controller that handles a small part of the overall plant as a single entity and optimises it to achieve an efficient operation following some certain criteria, like minimum energy, minimum waste products or maximum throughput of a certain stage. Many types of controllers can fall in this category, for example, Model Predictive Controller (MPC), Linear Quadratic Regulator (LQR) and Extremum Seeking Controller (ESC).

The optimisation based control can be model based on an approach which requires the knowledge about the system model (MPC and LQR) or it can be model by a free approach (ESC). The optimisation based actuates on a number of signals in order to achieve the required optimality. In most of the cases, the objective consists of many variables that are measured first, then the optimality criteria will be calculated, like the MPC and the LQR case, while is some cases, the optimality criteria can be measured directly, like in the ESC case.

2.3 Optimisation of Operation

This is the highest level of the control structure. It represents the plant wide control in the large scale. This layer will ensure that the optimal operation of the plant that is accomplished through the achievement of certain objectives. It uses the lower stage of control schemes to achieve the required optimality by passing a lower level set-points to the different small optimisation based control components as can be seen in Figure 6.

Figure 5: An example of low level control of flow. The control is actually of two stages of control for the flow and the position of the valve.

These types of low level controllers which act as a follower to the high level controllers can be varied between different types of controller, like PID, sliding mode controller and artificial intelligence controllers.
This layer might not be automated and the operators of the plants will generate the set points to the lower level controllers which might lead to a suboptimal operation of the plant. The operator normally looks into a steady state operation that ensures a stable operation of the plant based on the prior experience gained over the years but will miss the optimal operation of the plant due the time varying nature of the plant, the changing nature of the available resources and the variable nature of demands.

There are many types of operations’ optimisers, varying from simple optimisation algorithm working on simple static maps that represent the system, look up tables that show the optimality under different operational conditions, to highly complex algorithms like MPC (or economic MPC) that use dynamic models of the plants and use different types of forecasting to prepare the plant for the change of the operational conditions and the change of the demands. Thus, it is required to provide a Real-Time Optimizer (RTO) that considers all these variations and continuously adjust the control signals to achieve the requested optimality.
3 CONTROL CONFIGURATION SELECTION IN DHC

3.1 GENERAL ASPECTS AND FINDINGS OF CONTROL CONFIGURATION SELECTION

The CCS problem consists of selecting the connections between actuators and measurements which are present in the control system. An extensive survey on CCS has been created under OPTi (M Castaño, Birk, & Nikolakopoulos, 2017). The survey includes different families of methods for CCS and discusses a set of desired properties for CCS methods. Additionally, research challenges on CCS are discussed. In this subsection, we first discuss the research results in OPTi within the field of CCS. Later, we discuss the application of CCS on two processes from OPTi: The District Heating and Cooling network from Luleå Energi, and the cold water production operated by SAMPOL for the supply to the Son Llatzer hospital.

3.1.1 Research Results on Control Configuration Selection

Under OPTi, we have created results related to some of these challenges, including the following:

3.1.1.1 Robust CCS

The traditional control configuration selection methods are traditionally designed using linear process models. However, uncertainty is an inherent property of any model. Some sources of uncertainty affecting the models are: nonlinearities, sensor/estimation noise, simplified/unmodeled dynamics, faulty or low quality measurement data, or time-varying behaviour like wearing/substitution of components. Uncertainty can be captured during modelling by extending the nominal model with an uncertainty description. In OPTi, we have derived methods for the translation of this uncertainty description into uncertainty bounds on three different CCS tools.

In the publication by (Kadhim, Castaño, & Birk, 2017), a method for the calculation of the uncertainty bounds on the Relative Interaction Array has been introduced. In the publication by (Miguel Castaño & Birk, 2016), methods for the calculation of uncertainty bounds the Participation Matrix and $\Sigma_2$ have been introduced.

3.1.1.2 Guided CCS

The methods for CCS have significantly evolved in the recent times, to the point where the technology is sufficiently advanced for industry application. However, the delay between research, education and finally industrial application implies that the approaches in current industry are still profoundly ad-hoc.

Many are the CCS tools in the literature, however these methods are rarely put in practice in industry. It is of interest to create guidelines for the use of CCS methods in order to facilitate their use by plant engineers.

Despite the vast amount of methods for CCS, these methods are rarely used in industry, where loops are often closed based on know-how and geographical proximity. The current ad-hoc approach is therefore unreliable and is prone to inadequate solutions.

The application to real-life of the CCS methods is hindered by the large variety of CCS tools to be applied, which are often complementary. Little work has been published on describing guidelines for the combined use of CCS methods. Under OPTi, the publication by (M Castaño & Birk, 2017a) has recently been submitted, where guidelines for CCS are introduced and are applied to a real-life industry process: a secondary heating system.

3.1.1.3 Automatic CCS

Even with the introduction of guidelines for CCS, the real-life application is hindered by the number of process variables, and therefore we have investigated computer algorithms for CCS where computer reasoning and
calculations aid the designer. The created algorithms within OPTi have been reported by (Kadhim et al., 2017), by (M Castaño & Birk, 2017b), and by (M Castaño & Birk, 2017a). Two variants of algorithms have been studied: algorithms based on Relative Gains for the design of decentralized configurations, and algorithms based on gramian-based Interaction Measures (IMs) for the design of sparse configurations. These algorithms can be applied to the nominal process models, or to process models with an uncertainty description.

A comparison between both variants of methods follows:

- The method based on Relative Gains needs only the gains of the process, which is useful when limited plant information is available. The method based on grammian-based IMs needs a dynamic model of the process.
- The method based on Relative Gains can be used only for the design of purely decentralized configurations, whilst the method based on grammian-based IMs can be used to design both decentralized and sparse configurations.
- The method based on Relative Gains includes the testing of necessary conditions for stability/integrity, whilst the method based on grammian-based IMs does not include any stability/integrity test. Integrity is often a desirable property of a decentralized closed-loop system. A decentralized closed-loop system has integrity if individual control loops can be disconnected (e.g. for maintenance) while the rest of the system remains stable.
- The method based on Relative Gains can be solved using linear programming, even if it has a combinatorial nature. This means that the method can be efficiently solved. On the contrary, the method based on grammian-based IMs has to be resolved in a combinatorial fashion, which could be problematic if the computational resources are not sufficient.

3.1.1.4 Data-driven CCS

Using data-driven methods for CCS, the most important structural interconnections of the process can be revealed from a tailored experiment. The control configuration should consider those important interconnections. In this way, the control configuration can be determined without the need of parametric models.

We have under OPTi created algorithms for the estimation of IMs by (Miguel Castaño & Birk, 2016) and by (M Castaño & Birk, 2017b).

3.1.2 Application of Control Configuration Selection in DHC

3.1.2.1 Application of Control Configuration Selection to the District Heating and Cooling (DHC) Network from Luleå Energi

The algorithm created under OPTi for automatic CCS are currently being applied to a model of the District Heating and Cooling (DHC) network in Luleå.

The application of the automatic CCS methods to the DHC network gives new challenges which are currently under consideration due to the complexity of the model. Some of these challenges are:

- The DHC model includes both fast and slow dynamics, which have to be treated separately in order to avoid inaccurate results. This can be resolved by performing separate analysis at different frequencies of interest and appropriately combining the indications from these analyses.
The high order of the system leads to numerical errors when applying CCS methods (e.g. some of the eigenvalues of the observability and controllability gramians result negative, which is a numerical error since they must be positive). This is resolved by applying adequate model reduction steps as discussed by (MCastaño & Birk, 2017a).

The large number of inputs and outputs makes the CCS methods very sensitive to input and output scaling. The scaling for the DHC system has to be refined. In order to find appropriate scaling, the process data is under examination in order to find information on: i) normal ranges of variations of the inputs/outputs during operation, or ii) variances of the input/output signals during operations.

It is targeted to implement these new automatic methods for CCS in the software tool ProMoVis, where the DHC system is being used to validate this implementation. The algorithms are already implemented and disseminated to the research community through publications and efforts are being placed on disseminating software code. As example, a function to find control configurations with integrity has been shared in the MATLAB file exchange (https://se.mathworks.com/matlabcentral/fileexchange/62030-find-pairings-with-integrity-findici). Additionally, the software tool ProMoVis has already been adapted in order to be able to represent DHC systems. A new capability of ProMoVis has been created to be able to import models from Modelica. This was needed, since the DHC model was created with Modelica. In relation to the previous bullets, new adaptations in ProMoVis are currently being undertaken in order to deal with additional requirements imposed by the complexity of the DHC system.

3.1.2.2 Application of Control Configuration Selection to the Generation plant at Son Llatzer operated by SAMPOL.

The generation plant for Son Llatzer was thoroughly examined to investigate potentials for improvement which are aligned with the goals of OPTi.

After thorough discussions involving plant operators and engineers from SAMPOL and researchers from LTU, it was found of interest to investigate the cooling process formed by the connection of 5 parallel chillers. A simplified diagram of the cooling process is depicted below. The main unit of the process is the absorption chiller, which is run by the generator. If the absorption chiller is not sufficient to satisfy the demand, then one or more electrical chillers have to be connected. Currently, the automatic control of the flows through the chillers not satisfactory, up to the point where the plant is not run in closed loop. This means that the plant operators manually set values for the valves. In the current control configuration, the loops are closed in such a way that a set of four independent Single Input Single Output PID controllers are connected using the valves as actuators. All the PID controllers are using exactly the same measurement which is the aggregated flow of produced cold water. The reference for the produced cold water is set to match the demand from the hospital. A few problems are inherent to this configuration:

i) A high level of interaction is expected, since all the control loops are independently competing for the same input flow,

ii) All the control loops are attempting to control the same variable without coordination,

iii) It is of interest to place references to the individual flows through each chiller, which is not possible in the current configuration.

The solution to be investigated is to create hierarchical controller. The lower level of the hierarchy will be a controller with a configuration which is coordinating valves in order to mitigate loop interaction. The configuration of this low-level controller will be designed using the CCS methods which resulted from the research generated at OPTi. The higher level of the control hierarchy will be a supervisory controller which is deciding on the separate flow references which are given to the low level of the hierarchy.
3.2 DHC SPECIFIC DEVELOPMENT

Control configuration selection usually requires the engineer to run a number of different mathematical tools on either models or data from the DHC system and thereafter take decisions on control schemes based on the analysis result. In order to take these decisions expert knowledge in control configuration selection is needed. In order to facilitate these kind of decisions for a wider range of user with less expertise in the area, the tool ProMoVis was developed, see (Birk, Castaño, & Johansson, 2014).

The tool ProMoVis combines the visualisation of the real-life system with the abstract model view, which means that the user will be able to connect the abstraction with their working context. The connecting point for this are the variables that are available in the DHC system, as it is indicated in Figure 8. Therein, it can be seen that he variables are visible on all the layers and that the process model layer is representing a signal flow graph. Similarly, the control system is represented with its functionality (either as block-diagram or as a signal flow graph). The analysis which is conducted will make use of the information that is stored in the process models layer, control system layer and on the variables themselves. The physical process layout serves on the purpose of putting all information into the context.

Figure 7: The generation plant for Son Llatzer hospital
Figure 8: Principle idea of a scenario and the layering approach that is used in ProMoVis and that analysis results will be presented in different visualizations. The builder functionality supports the structuring and combining of the information and the analyser functionality processes and provides the user with information for the decision making.

A screenshot of the ProMoVis user interface and of a visualisation of an analysis result is shown in Figure 9. The example is one of the original use cases for the development of ProMoVis and taken from the pulp and paper industry, where properties and flows of a suspension need to be firmly controlled.

Figure 9: Screenshot of the user interface of ProMoVis (background) including a visualization of a control configuration selection result (front). The magenta arrows indicate the preferred connections of the process model for the controller design and the most feasible configuration, wider arrows indicate higher impact.
ProMoVis was originally developed for the process industry and therefore contains feature and interface components which are not applicable in the DHC area. Moreover, there was a shortcoming in ProMoVis when it comes to setting up a scenario for analysis, which is until now a manual procedure, including updating the scenario with new or changed models.

### 3.2.1 Import and update feature for ProMoVis

While ProMoVis facilitates the working steps tremendously, ProMoVis requires the engineer to manually setup the model for the DHC system. For models of the size of a full scale DHC system, this is not feasible, especially because any changes in the model had to be made in a manual fashion. The result would have been error-prone and tedious working steps that would eradicate the meaning with the ProMoVis. For this reason, an import and update feature for models is needed.

Moreover, OPTi-Sim makes use of automatically generated models in Modelica, see OPTi deliverable D4.3. These models are then used in Dymola from which FMUs for OPTi-Sim are generated. Most control configuration selection methods operate on linearized models, which are also used for control design. These type of models are hereafter referred to as control models. Modelica models are generally not control models and need to be approximated. Both Dymola as well as MATLAB provide functionalities that aid the user in approximating control models. These models are then easily exported from either MATLAB or Dymola, as they use the so-called state space realization of a linear system.

One of the main differences between simulation tools like the FMU toolbox in MATLAB/Simulink and Dymola is the fact that signals (or variables) are not categorized. From a simulation perspective it is not interesting to distinguish between different categories of variables. On contrary, in control configuration selection it is important to know how a certain variable needs to be treated or interpreted. The following categories are needed:

1. Controlled or measured variables (referred to as *Measured*)
2. Manipulated variables or control signals (referred to as *Control*)
3. Estimated variables (referred to as *Estimated*)
4. Disturbance variables (referred to as *Disturbance*)
5. Internal states (referred to as *Internal*)
6. Reference variables (referred to as *Reference*)

For example, a control configuration needs an interface from the process to the controller in terms of data that can be acquired to the controller and then an interface from the controller back to the process where actuation takes place. Since the Modelica models do not have a category property, this information has to be added by the user in between export and import. In the example in Figure 9, only three out of the total 6 categories are used, namely 1, 2 and 6.

In the state space realisation there are usually three categories which are called *Inputs*, *Outputs* and *States*. While *States* can be translated into *Internal*, *Inputs* can be *Reference*, *Disturbance*, and *Control*. Similarly, *Outputs*, can be *Estimated* and *Measured*. This distinction has to be added and maintained in a manual way. Either the export already contains a list or the import feature will have to request this information.

It was also decided that the import and update feature will be a stand-alone functionality. In that way, it is possible to choose to integrate the functionality into the export in MATLAB and Dymola, or into ProMoVis. ProMoVis stores its scenario files in an XML format, which enables the feature to simply generate an appropriate XML file that contains the exported model. The update feature on the other hand will need to parse the ProMoVis scenario file and update the model components that are already there from an earlier export. It was chosen to take this step, as an engineer might have manually added additional information to
the scenario file which is not contained in the model export, like for example the placement of the variables in relation to physical components.

As a result, the import and update feature are MATLAB scripts which directly operate on the exported information and a prior scenario file which is created from an earlier import.

3.2.2 Support for integrating processes

Most methods for control configuration selection cannot deal with integrating processes. Such processes are for example tanks and storages. The methods that enable control configuration selection on integrating processes are developed and published in (Arranz, Birk, & Asplund, 2015) and have been implemented in ProMoVis during WP5. All details on the methods and in what way methods were extended, is described in the publication.

The initial validation was conducted on a secondary heating system since models were already available and the DHC models were still under development. The additional functionality has no user interface and simply removes a shortcoming. It has to be noted that the applicability of the ProMoVis functionality is widened substantially and is critical for real-life application cases.

3.2.3 Preparation of pilot scenarios for analysis

When control models are available it is necessary to put them into the right context. While the control models are complete in the sense to perform analysis, the variables need to be related to physical component out in the field. This facilitates decision making and discussion immensely. In Figure 10, an adapted scenario for the Luleå Energi DHC system is given. First of all, the DHC net is displayed and variables are placed out in the DHC net as they are placed in real-life. Then the red arrows indicate the control models which are representing the dynamic behaviour of the DHC system.

Figure 10: Adapted interface for ProMoVis with a partial DHC model for the Luleå Energi AB DH system imported. The red arrows show the available interconnections in the model between the variables that were available in the exported model from Dymola and from the FMU toolbox of MATLAB.
Now, the analysis of the complete system to determine a feasible control configuration can be performed. It is also possible to evaluate the current control configuration if it is adequate based on the analysis result. In the visualisation different parts can be enabled or disabled for the view, based on the needs of the discussion. When the scenario is completely set up, it is possible to update the models using the update feature and no additional work is needed to update the scenario. The visual appearance will remain the same.
4 AUTOMATIC SYNTHESIS OF SUBSTATION CONTROL LOOPS

Building substations have the task to provide a building with a desired amount of heat and hot tap water at a specified set point temperature. The substation comprises a number of hardware components like pipes, valves, pumps, heat exchangers and sensors, as depicted in the piping and instrumentation diagram in Figure 11.

![Figure 11: Principle sketch of a building substation with space heating and tap water circuit. Hardware components (solid lines), control system components and sensors (dashed lines).](image)

There, it can be seen that the control of the substation is done in a decentralized fashion, where the hot tap water control circuit operates independently of the space heating circuit. Since both control loops operate on the same heat source, these loops will interact and could render oscillations in the desired hot tap water temperature or supply temperature for the space heating, denoted by $T_{SP}$. Traditionally, these controllers are implemented in separated controller boxes or as an enclosed control system which provides the engineers with limited opportunities to improve the control strategy. The overall control architecture for a typical substation is then depicted in Figure 12, where the vector signals $d$ and $y$ represent disturbance signals and measurement, which are not part of the control loops, respectively.

![Figure 12: Block diagram for the substation depicted in Figure 11 assuming $T_{Bias} = 0$, with the individual controllers for space heating $C_{SH}$ and hot tap water $C_{HW}$, and the dynamics of the substation represented by the model $G$.](image)

In more modern solutions it is common to integrate more measurements in the control strategy, e.g. flow measurements on the tap water side to use them in disturbance rejection schemes. Another option is to
control the temperature for space heating and hot tap water jointly, which can circumvent the effect of the interaction of the control loops. In these cases additional interconnections in the control system appear.

A typical problem in this context is the synthesis of the individual controllers and to keep the controllers and their parameters up to date with the hardware of the substation. It is well known that a change in hardware adversely affects the performance of the closed loop systems, which means that the set points are not well tracked or that disturbances are not swiftly attenuated by the control system. In turn, users might experience discomfort or that heat is not used in an efficient manner, rendering performance limitations of the overall system.

Automated synthesis of controllers that support engineering and building managers in their effort to keep the controller up to date would reduce efforts and enabling better performing building substations. In (Birk & Atta, 2016), the basic principles for an autonomous synthesis of building substation control loops is described. The principle idea can be captured in the following steps:

1. **Discover and quantify insufficient control loop performance.** The current performance has to be assessed and put into relation with the desired performance of the control loop. The performance can be quantified in terms of tracking and disturbance rejection performance as well as actuator usage. It is necessary to distinguish if performance issues arise from hardware or controller tuning. In the latter case, the engineer can directly continue to the next step. Otherwise, hardware might need to be replaced prior to continuing to the second step.

2. **Determining a dynamic process model for the substation behaviour.** For any systematic control design, there is a need to have a dynamic process model available to design and synthesize a controller which attains desired performance characteristics. The models can be either derived from acquired data or as a hybrid approach from first principles in combination with data.

3. **Automatically synthesize the substation controller.** The user provides the desired performance characteristics, controller type and based on the process model the controller is synthesized. The user will get the resulting controller parameters that can be used in a substation.

4. **Storage of results.** The resulting process models, data, component information on the building substation and resulting controller will be stored for later reference or usage.

In the sequel the different steps will be discussed in more detail and a prototype tool is discussed.

### 4.1 Issues in Building Substation Control Loops

Over the life cycle of a building substation, the requirements on the substation change. One important factor that has a large effect is the reduction in energy consumption of building or the behavioural change of the users in their consumption of hot tap water. While the building might be changed and behaviours adapt to a changing environment, the substation might remain unchanged.

A consequence can be wrongly dimensioned valves, pumps and pipes, which directly affect the performance of the closed loop system. Oversized valves in combination with control systems that have fixed resolution of the measurement and control signal can render limit cycle behaviour. Such limit cycles lead to oscillations in controlled variables like supply temperature $T_{SP}$ or hot tap water temperature $T_{HW}$. While the energy consumption in average remains the same, excessive valve wear might occur. An example of such a situation is shown in Figure 13, where the resolution of the actuator signal limits the performance of the closed loop system.
Figure 13: Example for a control valve with limit cycling behaviour and minor but excessive valve motion at a substation in Porsögården, Luleå, Sweden. Valve opening (left), hot tap water temperature (right).

Moreover, changes in the substation or the building will yield a different dynamic behaviour and the current controller might not be well adapted to the new situation. In these cases tracking of set points and rejection of disturbances is not achieved in a timely fashion and tuning of the controlled should be performed.

Figure 14: Data from operation of the substation at Traktorvägen, Luleå, Sweden. Valve opening (left), hot tap water temperature in blue and its set point in red (right).

In Figure 14, it can be seen that the hot water temperature is fluctuating in a large range around the set point, due to disturbances in the form of hot water tapping. The temperature deviates as much as five degrees from the set point and only rarely varies in a small range around the set point, which indicates that the substation has limited abilities to reject disturbances. Moreover, the actuator is moving quite slowly, while the hot water temperature is fluctuating over a relatively wide range, as can be seen in the beginning of the sequence. If the controller is tuned to rapidly reject disturbances, the control valve will have to move faster and be more aggressively. In other words, if the control architecture is not changed and considering secondary measurements, which would indicate the early occurrence of a disturbance, the performance improvement will be limited and comes with a higher wear of the control valve. In the shown example, it would be advisable to change the control architecture, by adding a feed forward action from a flow measurement of the tap water. While this is possible in modern substations, in older substation hardware changes are needed.

Finally, in the last example it is unclear to what degree the space heating control loop is interacting with the hot tap water control loop. If the space heating control loop is active in the same time scale as the hot tap water control loop, it is highly likely that the loops interact. In that case, $C_{SH}$ and $C_{HW}$ can start to counteract and will render oscillations in the controlled variables. The cause of the interaction lies in the extraction of heat from the same source, which is in the incoming hot water from the DH system. In the worst case, this interaction can generate pressure fluctuations back into the DH system. In order to isolate this problem an interaction analysis need to be performed and a control configuration selection for the substation will provide an indication. As a result, a multivariable controller for the substation would need to be designed.
4.2 **DISCOVER AND QUANTIFY INSUFFICIENT CONTROL LOOP PERFORMANCE**

The performance of a control loop can be defined in different ways. First of all, there is the requirement that is put on a closed loop system and in what way disturbances are rejected and set point are tracked. As the desired performance can be unrealistic in relation to used hardware and the phenomena that is controlled, the achievable performance is usually a better and more realistic indicator to compare current performance with.

Unfortunately, achievable performance is an indicator which is difficult to derive and depends on a number of factors that involves system properties, here properties of the substation from a hardware perspective, and choices in the control design, here individual control loops versus multivariable control loop. Any of these properties limits the achievable performance. The current control loop can be understood as operating optimally, if the current control loop is close to the achievable performance. If this control performance is insufficient, then a mere tuning of the controller will not solve the performance problem and an upgrade of either control architecture or hardware is necessary. In the context of the autonomous synthesis of controllers, the upgrade of hardware and control architecture is not within the scope of this algorithm. Nevertheless, a decision has to be taken if the controllers can be tuned or not.

Already in (Harris, 1989), Harris developed a performance assessment technique using data from normal operation for univariate control loops both in SISO (Single Input-Single Output) and MIMO (Multiple Input Multiple Output) system. The evaluation is based on the variance in the closed loop system, where minimum variance control is a natural choice, see (Huang & Kadali, 2008) for more details. The key concept in Harris work is to identify if the cause for poor loop performance is due to the current controller design or due to external disturbances. The procedure enables the diagnostics of the cause for the performance deficiency.

While such algorithms are nowadays available in most commercially available DCS, substation controller lack such features. Moreover, the online analysis of the performance is not needed and it is sufficient to perform the analysis in an offline tool where acquired data from operation is used and the diagnostic is presented to the engineer. A further development of algorithms for performance monitoring is judged to be out of scope and available algorithms should be applied to the building substation control scenario.

4.3 **DETERMINING A DYNAMIC PROCESS MODEL FOR THE SUBSTATION BEHAVIOUR**

As already indicated above, the building substation is a multivariable system, also referred to as MIMO (multiple-input multiple output) system. Usually, modelling of individual interconnections one at a time yields to larger modelling errors than modelling the complete system directly when the system has strong cross-connection. In case of the building substation, it is reasonable to assume that the system has weak cross-connections between space heating and hot tap water, while the hot tap water control is largely effected by the disturbances such as hot water tapping.

Moreover, the hot tap water control loop and the space heating control loop do operate in different time scales, namely the space heating control loop will act far slower than the hot tap water control loop. As a result, the interaction between the loops can be modelled as a disturbance instead of loop interaction.

4.3.1 **Process models from experimental data**

A limitation in the experimental setup is often the fact that control loops cannot be taken out of operation which results in higher requirements on the system identification (learning) of parameters in either a grey box model or of the black box model. Simply using actuator and measurement signals for the system identification can render biased results for the parameter estimation. A good summary of the topic can be found in (Forssell & Ljung, 1999).

In order to circumvent this problem, it is necessary to tailor experiments which create sufficient excitation of the control loop, to enable an estimation of the parameters. In Figure 15, a simplified loop setup is shown.
There, it is assumed that $C$ represents the controller of a temperature $T$ with a set point $T_R$. In relation to Figure 11, the pairs of measurement and set point could be either $(T_{SP}, T_{SP,R})$ or $(T_{HW}, T_{HW,R})$.

Figure 15: Simplified loop setup for the parameter identification of a dynamic process model in a building substation. Wide arrows indicate vector signals, while normal width indicate scalar signals.

Determining an accurate process model $G$ will therefore rely on sufficient excitation in $T_R$, which is usually not present in operational data. A common mistake is also to provide an excitation signal as an offset on the actuator signal (often possible in control systems) and thereafter use the actuation and measurement signal straight away. As a result, the identified process model is not representing $G$ but $C$ instead. Nevertheless, if the controller is well tuned then the time constants in the controller often reflects the time constants in $G$, while the identified gain constants become wrong. Thus, experiments have to be conducted with care and the closed loop in mind.

In order to derive the model $G$, the following approach is taken as discussed in (Birk & Atta, 2016):

1. An experiment is conducted where the closed loop system is excited by a set point signal $T_R$, which can be a multi-step sequence. The sequence must be sufficiently long to produce both training and validation data. During the experiment, the signals $T_R, T$ and $u$ are logged simultaneously.

2. The current controller which is in operation during the experiment is extracted. Usually, standard P, PI, PD or PID type controllers are used. The parameter setting for the controllers and their implementation need to be noted down.

3. Using system identification algorithms, the parameters of the closed loop system

   \[ P_T(s) = \frac{G(s)C(s)}{1 + G(s)C(s)} \]

   can be estimated. Since the model for the controller is known, only the model structure for $G(s)$ need to be assumed. Here we assume that the system is composed of a heat exchanger and a flow control valve, which can be approximated by two prototype models

   \[ G_{P1D}(s) = \frac{Ke^{-\frac{Ls}{\tau}}}{{\tau s + 1}}, \quad G_{P2Z}(s) = \frac{K(\tau_1 s + 1)}{(\tau_2 s + 1)(\tau_3 s + 1)}. \]

   It can be noted that the model $P_T(s)$ has a known structure for the system identification, which also means that the experiments can be tailored to be informative and sufficient excitation properties can be guaranteed.

4. When $P_T(s)$ is found, the model $G(s)$ can be calculated by as follows

   \[ G(s) = \frac{P_T(s)}{C(s) - P_T(s)C(s)} \]

   Now a black box model for either the space heating or the hot tap water system is found and can be used in the controller synthesis.

4.3.2 First principle modelling in combination with data-driven approaches

An alternative to the black box modelling approach is the usage of a grey box approach. In the grey box approach the main parts of the model are derived from first principles and some unknown parameters are then derived using system identification methods where either experimental data or operational data is used.
At this point it has to be kept in mind that both, the experiments as well as the operational data, need to excite the system such that the sought parameter values can be estimated. Depending on the model and its structure, the experiments can become complex and difficult to perform. Moreover, operational data might be non-informative and the estimation will not render trustworthy model parameters.

In the design of a substation there are a number of assumptions made on a number of nominal variables that render the dimensioning of the components of the substation. Here, the differential pressure, supply temperatures, return temperatures and flows are critical values. Those can be used to understand the operational conditions of the substation, as operating points.

As a result, the known valve dimension \( kv \) and \( kvs \) are chosen. Moreover, from the supplier of the valve, the valve curve and the rate limitation are available. By that, the valve is more or less completely defined.

For the heat exchanger, the situation is different. A heat exchanger has far too many parameters that affect the behaviour and the operating condition largely effects the dynamic behaviour. Thus, an approximate model needs to be defined which uses operational data from valve opening, differential pressure, supply and return temperature as well as cold and hot water temperature. Not all of these measurements are available in a standard building substation, which would mean that the model quality could become low.

More specific experiments need to be conducted and analysed to get a full understanding if the approach is feasible. These investigations are judged to be out of the scope of WP5 and will be conducted during WP6.

### 4.4 Automatic synthesis of controllers

Now that a model \( G(s) \) for either the space heating control loop or the hot tap water control loop are available, a new controller can be synthesized. In order to determine the controller, knowledge about the desired responsiveness is needed. There are a number of ways to characterize this property, where settling time \( \tau_{ST} \) of the closed loop system is one and the desired bandwidth \( \lambda \) is another. It needs to be noted that a faster response will render a more aggressive controller, which needs to be taken into consideration by the engineer.

Depending on the implementation characteristics of the substation controller there are different options for the controller design. If the substation only offers a 1-DOF controller architecture with a PID-type controller, the design is predefined and the synthesis of the controller is reduced to the derivation of the PID-type controller. In this situation the controller cannot make use of a disturbance feedforward, even if the disturbance could be measured. The situation is different when either a feedforward action can be designed or the controller implementation is freely programmable. Usually, a 2-DOF controller architecture can be used with optional feedforward action from a disturbance measurement/estimate.

#### 4.4.1 Synthesis of a 1-DOF PID-type controller

Depending on the chosen prototype \( G_{P1D}(s) \) or \( G_{P2Z}(s) \), the controller can be synthesized as follows.

In case of \( G_{P1D}(s) \) it is sufficient to synthesize a PI Controller. The controller could be tuned using the \( \lambda \) –tuning method or simply based on a generic internal model control design, see e.g. (Skogestad & Postlethwaite, 2007). During the design the desired settling time or bandwidth \( \lambda \) is another. It needs to be noted that a faster response will render a more aggressive controller, which needs to be taken into consideration by the engineer.

In case of \( G_{P2Z}(s) \) a PID controller can be synthesized based on the internal model control design. There the controller can be based on

\[
C(s) = k_p \left(1 + \frac{1}{T_I s}\right).
\]

In case of \( G_{P2Z}(s) \) a PID controller can be synthesized based on the internal model control design. There the controller can be based on

\[
C(s) = \frac{1}{G_{P2Z}(s)} \frac{1}{\lambda s}.
\]
if the $G_{P2Z}(s)$ does not contain a right half plane zero (the roots of the transfer function’s numerator that have a real positive value). In case of a right half plane zero, which means that the system exhibits non-minimum phase behaviour, the zero needs to be excluded in the control design such that

$$C(s) = \frac{(\tau_2 s + 1)(\tau_3 s + 1)}{K} \frac{1}{\lambda s}.$$ 

As a result, the right half plane zero is retained in the closed loop system and that behaviour persists. The resulting controller will then be a PID controller in the latter case and in the first case a filtered PID controller. It is important to note that instead of the design based on internal model control or $\lambda$-tuning, an optimisation based approach to determine the controller parameters can be chosen. In that case, the performance specification can be translated in constraints on the time response or the frequency domain response. An advantage of that approach is the possibility to consider actuator constraints in the synthesis of the controller.

### 4.4.2 Synthesis of a 2-DOF controller with feedforward action

In the two 2-DOF control architecture setup, the disturbance rejection properties can be shaped independent of the tracking properties. Moreover, the use of a feedforward action is beneficial for the fast recovery from disturbances. The architecture is given in Figure 16 and contains two additional components in the controller, namely $F$ and $C_{FF}$.

![Figure 16: 2-DOF control architecture with a tracking filter $F$ and a multi-input-single-output feedforward filter $C_{FF}$](image)

The additional components enable the shaping of the dynamic response. $F$ enables the shaping of the response to changes in set points, while $C_{FF}$ enables early control reactions to disturbances before the effect can be observed in the measured temperature. The synthesis of $F$ can be done after the synthesis of $C$ and targets a smooth transition to the new set point while keeping the control signal small during the transition. In order to design $C_{FF}$ a disturbance model needs to be available. Since the disturbance has to be measurable or at least estimated from other sources a model could be derived, while disturbances of sufficient excitation are acting on the system.

The synthesis of $C$ can be conducted in the same way as for the 1-DOF case. The synthesis of $C_{FF}$ usually involves the use of an inverse of the identified disturbance model. Since those $C_{FF}$ are difficult to realize due to non-causal portions, a causal approximation of the filter has to be determined. The most simplistic way of getting a causal realisation is by adding low pass filters of sufficiently high order and sufficiently high bandwidth to contain the non-causal parts. The disadvantage of that approach is the relatively high order of the resulting filter.

### 4.5 Practical aspects and storage of results

When it comes to the space heating case, tracking properties have a higher importance than the disturbance rejection properties of the loop. The reasons is found in the structure of the heating circuit which contains radiators with thermostatic controllers. Those thermostatic controllers represent an inner loop of a cascade, which deals with fast disturbances, while the outer loop provides the heat which is needed for the space heating task. It should also be kept in mind that space heating is a slow control loop, which generally does not require fast control action on either disturbances or set point changes.
The situation for the hot tap water circuit is somewhat different. Normally, the set point for the hot tap water is not changing or only rarely, while disturbances in the form of hot water tapping is occurring very fast and often during a short period of time. Smaller buildings with few hot water consumers have the most adverse situation, as the consumption is not sufficiently superimposed to smoothen the disturbance peaks. A good indicator for the demand is the flow on the secondary side of the heat exchanger, which can be used as to calculate a feedforward action. For this end a flow measurement on the secondary side needs to be available. Other secondary measurements that could provide an indication for hot water tapping would also facilitate the situation and could be used to estimate the disturbance.

As a result, it is reasonable to assume that the space heating and hot water circuit do not interact sufficiently much, which would require a more advanced control configuration than two single-input-single-output control loop, a so-called multi-loop configuration.

An important aspect is also the management and storage of the results. The different steps render a number of intermediate results which could be re-used at a later stage, but are also important for the purpose of comparison of control loop performance and controller tuning over time. Thus, all results derived from experiments, data analysis, component analysis, models, desired performance specification and resulting controllers need to be stored. Naturally, it is up to the engineering of the utility company to derive an appropriate strategy for the data storage.

4.6 INTEGRATED TOOL WITH A GUI

The automatic synthesis of substation controllers involves a number of steps, where certain selections need to be made by the engineer. While the intermediate calculations can be well automated, the user input cannot. In order to facilitate the usage of the tool a GUI will aid the engineer in taking the appropriate decision and selections on the way.

The following functionality has been identified together with engineers at the involved utility companies:

- Import and export of experimental data and operational data in different formats. The format list shall at least include Excel spreadsheets, text files with different types of delimiters between values (comma separated or tab separated).
- Storing and loading of an auto-tuning session with all its values. Preferably a once created session could be used as a template for other sessions. Here, a word of caution has to be raised. Templates have the tendency to enable the engineer to reuse settings which might not be feasible for the case that is dealt with at hand.
- Modelling based on data and on component information should be possible to be conducted in parallel. This means, one session can contain both types of approaches as discussed above.
- Substation templates are needed to facilitate the modelling which is based on component information. Such template should only contain information on component which are used in different substations over and over again.
- Choice of model prototype $G_{PD1}$ and $G_{PD2}$ for the modelling
- Choice of controller type: P, PI, PD, PID and I.
- Choice of synthesis method: internal model control and optimisation based.
- Setting of loop performance characteristics.

Based on these functional requirements a GUI was designed and the underlying algorithms were connected to the GUI. All algorithms were implemented in MATLAB and the GUI was realized using the user interface design features in MATLAB, see Figure 17. A standalone version of the tool with GUI can be created using...
MATLAB Compiler tool suite, which is not within the scope of WP5. In that way, a preliminary integrated tool with GUI was designed, which can be used by the industry partner on dedicated computers.

Figure 17: Screenshot of the Substation Tuning Tool. Plots on the left show the temperature measurements on the top and the control signals on the bottom. The screenshot shows the imported data from an experiment conducted at Luleå Energi AB.

During WP6 the tool will be tested more thoroughly by the industry partners and adaptations based on their user experience can be implemented.
5  PREDICTIVE CONTROL FOR PEAK LOAD REDUCTION AND OPTIMAL OPERATION

The major development in the last decades in the computational power and the understanding of complex processes lead to new developments in the possibilities of controlling the plants. One of the most interesting aspects in automatic control is the Model Predictive control. In General, the classic method of closed loop control of plants uses the model (or an approximation) of the plant during the design phase of the controller, afterwards, a controller is designed. Also, at run time (the online mode), the controller will be connected to the plant and will control a number of variables (plants inputs) in order to derive the system outputs to track a certain requirement (references). Knowing that, the controller will be fed with only the current requirement signal (references). Figure 18 shows the concept of the classic control scheme. An example of this type of controllers is the PID controller, which is widely used in the DHC network, for example controlling the pumping stations and control the flow through building heat exchangers (Camacho & Alba, 2013).

![Figure 18: Classic Control Schemes](image)

Although, the classic approach is simple and easy to implement, it has three main limitations,

- The Model of the plants is not utilized enough. If the plant model is available, it is possible to predict up to a certain level of accuracy the plant output. The prediction accuracy actually will depend on the accuracy of the model itself. Thus, why not utilize this fact during the run time?
- The controller uses only the current sample of the requirement signal (references) while in many plants, the reference signals can be known in advance. Thus, why not use the forecasted requirement signal in advance?
- The plant limitation, if any exists, are handled by another layer that will prevent the system entering a certain state, like not reaching a certain temperature or pressure and the limitations are not considered by the controller operations. Thus, if these limitations are known in advance, why not select the actuating signal values such that these limitations will not be violated?

The model predictive control can be simplified as the fact that if you have the knowledge about your system model, then the plant inputs can be designed to achieve a certain criteria (objective) such that the plant limitations will not be violated. This objective can be described as the deviation from the required output or the energy consumed by the input. The objective is not consider that current (instantaneous) values of the input and output, but it can include the future values up to a certain horizon (Camacho & Alba, 2013).

The basic elements of the MPC controller:

- Prediction model: Plant model (Process model) and Disturbances model
- Objective function
- Limitations (constraints)
- Optimiser: Obtaining the control law
The optimiser will operate to find the optimal control signal that will optimise the given criteria without the violation of the plant limitations. Figure 19 shows a typical structure of the MPC controller.

![MPC Control Scheme](image)

*Figure 19: MPC Control Scheme*

The MPC can be used at various levels with different time scales. Also, it can be used at the different parts of the DHC plant: at the building level to provide the required demand in an optimal and efficient way, at the distribution network to provide an optimal pressure distribution and at the generation parts, to provide the optimal operational scenario at different operational conditions (Jing, Jiang, Wu, Tang, & Hua, 2014).

### 5.1 Controlling the Buildings

The current building control scheme is based on a knowledge based approach that correlates the outdoor temperature to the secondary side of the heat exchanger at the building (Gustafsson & Delsing, 2008). Similar to the generation side, the supply temperature of the secondary level has a look-up table that is based on prior knowledge and shows an optimal value of the secondary side temperature as a function of the outdoor temperature. Then, a controller will adjust the control valve opening to achieve the prescribed supply temperature. The main drawbacks of this approach are that it is not related to the actual indoor temperature, it does not count any economic factor and cannot avoid peaking the demand due to rapid changes in outdoor temperature.

![Classic HDC substation control](image)

*Figure 20: Classic HDC substation control. The control scheme is based upon a look-up that shows the optimal relation between the outdoor temperature and the Heat Exchanger (HEX) secondary side flow temperature. The controller will adjust the control valve to achieve this temperature.*
The adoption of MPC can bring many features that will help to improve the performance of the plant by introducing

- Dynamic comfort zone: The user comfort zone can be adjusted dynamically according to the user requirements. The comfort zone can be varied over the day, the week and the season. These comfort zones will be the constraints.

- Weather forecast: The outdoor temperature is defined as a key point in this approach. The building model is using the outdoor temperature to define the possible cold/heat energy loss. The future planning which is the important feature of MPC will be depend on the forecasted weather. Note that the MPC does not require that the forecast will be very accurate and the variation will be handled due to the iterative nature of MPC.

- The consumption: The consumption can be treated in different ways. It can be added as a limitations (constraints) and/or it can be included in the objective criteria with the dynamic cost of energy to minimize. Also, in case of shortage in the cold/heat generation, the generation subsystem can provide a feed forward notification to the MPC to prepare for the upcoming shortage and to take an advance step.

Using MPC can improve the consumption profile through shifting the peak of loads into different hours through adjusting the comfort zone, prepare for the shortage of generation in advance and economically optimise the energy consumption.

**Figure 21**: MPC to control the heating system in a building.

5.2 **CONTROLLING THE PRESSURE IN THE NETWORK**

For the large distribution network, the main objective of the pumps is to keep the pressure level to be at a certain level at different points in the network. The current control technology is based on the fact that each pump should control a number of points such that these points should not get below a certain level. The current control strategy as explained above is by taking the minimum of a pressure at some points in the grid then feed it to a PID controller that controls a pump in the grid. The point is that the relation between the pumps are correlated (as explained in the control configuration section) and there exist some interactions between the pumps. The current control approach is shown in Figure 22.
The main drawbacks at the current control strategy are:

- The interactions between different pumps cannot be isolated. These interactions might lead to some oscillations in the network.
- The level of the different points and the use of the minimum signal will ensure a below limit for the pressure in the network but does not ensure an above limit.
- The joint operation of the pumps is not optimal. It is true that the network might reach a state that provides the required pressure, but this does not mean an optimal operation. This is since the pumping directions in some regions cannot be cooperative.

![Diagram of DHC network and pump operation](image)

**Figure 22:** Current control structure of the pressure control structure

The optimal way to operate the plant is to consider the operation of all the pumps together through the adoption of a swathing MPC controller. This will provide an optimal operation that will minimize the wrong interactions between the pumps. Since the selection of the operational pumps will be selected by the plant’s operator (i.e. the decision of the pumps to be on or off is decided by the operators and in most of the times it follows the operation of different energy generation units), the MPC’s model will be different for each combination of pumps and generation units. Thus, the first step in designing these pumps is to define all the possible combination of the operation of the plants. Then a linearized model will be defined for each operational scenario. Then the switching MPC will use these models and the selection of the right model will be triggered by an external signal. The optimality criteria of the MPC can include the energy consumption by the pumps and the set points of an important pressure point in the grid. The constraints (limitations) of the MPC controller can be the pressure levels of different points in the grid and by these constraints the optimal pressure profile in the grid can be achieved.

### 5.3 Controlling the Plant Operation

This joint operation of different unit is one of the most important points in any multi-generation plants. The selection of the optimal combination of units that will provide the optimal and efficient operation of the plant is currently executed based on the knowledge of the skilled operators of the plants and normally the selection of the unit and the timing of putting the units on or off is varying from one operator to another.

The MPC controller can be used in this case such that the optimality criteria will be the minimum energy consumption of the units while all the demands will be presented in the constraints of the process. Like the building MPC, the weather forecast will be integrated within the plant models. The periodic behaviour of the plants (for example the starting of different cooling units in the morning and turning off in the evening at Son...
Llàtzer hospital in Mallorca) can be included as a forecasted demand model that will be integrated with the plant’s dynamic models (Jing et al., 2014). The use of the MPC controller with the integration of these two forecasts will lead to the following improvement:

- The dynamic optimal operation scenario can be achieved.
- The optimal timing for turning different units on and off can be achieved.
- The optimal criteria can include several factors like environmental impact minimization, the equipment’s wear minimization, energy reduction and profit maximization. These objectives can be combined into single objective (weighted combination) or treated as multi-objective optimisation criteria.
- The forecasts will help to overcome the possible shortage in the heat/cold generation and can provide load shaving by providing a nonlinear weighting on the energy consumed. This will improve the performance of the overall plants especially when the generation units have different efficiencies and use different type of resources.
6 SEEKING CONTROL AND APPLICATION IN DHC:

This approach presents a low-mid level optimiser of unknown dynamic plants. The controller will adjust the plant input and drive the system to achieve the extremum (maximum or minimum) of the plant input(s) which represents the objective(s) like the plant throughput, energy consumption or used resources. The process can be single objective like in the case of the Extremum Seeking Control (ESC) or multi-objective like the Pareto Seeking Control (PSC).

The seeking control is utilized by the addition of a perturbation dither signal to the plant inputs, then a gradient estimator is adopted and finally the plant will be steered to achieve the requested optimality based on the gradient estimation depending on the number of objectives. In the single objective case (ESC), a simple integrator or a proportional integrator is adopted to control the plant inputs until the gradient reaches zero while in the multi-objective case, the control inputs will be adjusted until the system reaches the pareto front, which is the collection of the weakly pareto point (at weakly pareto point it is not possible to improve any objective without the deterioration of another objective).

![Gradient Estimator](image)

**Figure 23:** Seeking control concept. The left figure shows the basics of ESC and the right figure shows the basic concept of PSC for 2X2 system.

6.1 THE APPLICATION OF SEEKING CONTROL IN DHC PLANTS:

The seeking control will be used at the lower level of the optimisation based control. It enables the optimisation of different objectives in the process. The seeking control can be used at different points in the grid like the optimisation of the energy consumption in a house or the minimization of the return temperature or the increment of the difference of the DHC supply-return temperature ($\Delta T$). The pareto seeking control will be applied to optimise different aspect simultaneously like the optimisation of the minimum energy consumption and the reduction of the return temperature. In fact, the pareto seeking control can be used in control aspects where multiple contradictory set points are requested and cannot be met simultaneously. For example, consider it is requested to achieve a certain flow at the plant and at the same time it is required to achieve a certain temperature. In this case, it is not possible to achieve both requirements at the same time. In the classic approach (MPC or the LQR) the two set points will be combined with a weighting factor (weighting the objective) to produce a single objective, then the controller will try to optimise this objective and the system will reach a fixed point. On the other hand, the PSC can be used to drive the system to the pareto optimal point with the need for the weighting factor. In that case, the system will be driven to the nearest pareto front and not necessarily the same fixed point.
6.2 THE COMPARISON BETWEEN MODEL PREDICTIVE CONTROL AND SEEKING CONTROL

Although the two techniques are both optimisation based control models, they have a totally different basis. The MPC is a concept that relies heavily on the models of the plant, it is the basic building stone in the concept and the knowledge of the model of the system will achieve an optimal performance. While the seeking control on the other hand is a model free approach where the full knowledge about the models is not required.

One of the disadvantages of the seeking control is the slow response and the requirement for the addition of a large perturbation signal to improve the performance compared to the MPC control. Due to that fact, the system knowledge will be acquired during the operation by means of the additional perturbation signal. These two subjects where addressed in this project and a fast seeking control was founded (Atta & Guay, 2017) and the adaptive amplitude was found in (Atta, Hostettler, Birk, & Johansson, 2016). These two approaches will help for a faster and less perturbations seeking control.

There are two other differences between the two approaches: For the seeking control, the constraints are not fully addressed, whereas for the MPC, any type of constraints can be defined, provided the ability to measure the internal states of the plants that are required for these constraints.
7 SERVICE ORIENTED ARCHITECTURE IN DHC SYSTEMS

The ideas behind OPTi being interlaced with those of Service Oriented Architecture (SOA) project a natural and straightforward concept. To reinforce this paradigm, we begin by reviewing several ideas, which include OPTi and SOA, to understand how we can achieve a System of Systems that ensures end users comfort while reducing energy waste and negative environmental impact. In this review, starting with district heating and continuing with SOA, we at times consider words to remind us of what we mean by them. When addressing SOA, we consider also issues of security, scalability and interoperability. Finally, we describe what is being done within the OPTi project to interlace these concepts.

The vision of the OPTi project is summarized as: creating a long-lasting impact by rethinking the way District Heating and Cooling (DHC) systems are architected, controlled and operated. The overarching goal is to create durable business benefits for the relevant industries, with ensured optimal end-consumer satisfaction and engagement, while operating these systems in an environment-friendly manner. To this end, we aim to use predictive control and automated heat Demand Response methods, while exploiting passive heat storage capabilities.

District heating is a centralized heating system that heats up a whole district from a central heating source, with district cooling being more or less the same thing but to cool down buildings when the weather is hot. The major appeal to district heating is that it is more efficient than smaller heating systems, (e.g., one heating system per building, or even worse, apartment or room) (Frederiksen & Werner, 2013). The concept is even more evident when this heat is an industrial by-product, such as is the case in Luleå, where the heat originates from the burning of low energy gases of a large steel plant. The reality is even more exciting since electricity is produced at the same time (combined heat and power, CHP, plant) resulting in an efficiency over 95% of a gas that would otherwise be emitted in the atmosphere.

One problem with heat energy production is the variation of its demand, especially regarding the consumption of domestic hot water. When too many people want to take a shower or cook at the same time, it is hard to meet the demand. This can be furthered aggravated by large swings of outdoor temperature. In district heating, one can see daily peaks of heat energy demand usually occurring in the morning as a district gets ready for work and school and in the evening around dinner time. When considering electricity, the same demand peaks also exists, so a CHP solution might be ideal until one realizes that the distribution of the two energy forms have different distribution speeds. In comparison, district heating is extremely slow as the energy is transported by fluid that needs to be pumped. It is here that we can begin to appreciate the OPTi project. How should one coordinate production, distribution and consumption to achieve harmony?

1 http://www.opti2020.eu/
Looking into district heating, one can break it down into four parts. Three of them are obvious: production, distribution and consumption. Figure 24 shows a SysML\textsuperscript{2} block definition diagram (bdd) of such a break down. The fourth block is composed of system’s management, e.g., billing, but also simulation to optimise the balance between the three other parts while prioritizing the end-users’ comfort as well as that of the environment.

This idea of online simulation and predictive control has become possible nowadays due to Cyber Physical Systems (CPS) and the Internet of Things (IoT).

7.1 **The 4th generations context**

The word cyber in CPS points to cybernetics. The term cybernetics is often used in a rather loose way to imply “control of any system using technology.” The US National Science Foundation (NSF)\textsuperscript{3}’s current definition of Cyber Physical Systems is: Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components\textsuperscript{3}. It is a definition that has evolved with time, and can be tracked by looking list the list of NSF funding program on the topic. The concept is a revolution in itself as it totally reinvents our industrial world. Two such actual examples are the Industrie 4.0 and the 4th Generation of District Heating (4GDH) (Lund et al., 2014). Industrie 4.0 is the German vision for the future of manufacturing where smart factories use information and communications technologies to digitize their processes and reap huge benefits in the form of improved quality, lower costs and increased efficiency. A specific industry is the heating industry, which is entering in its 4th generation. The 4DH Research centre\textsuperscript{4} defines the 4th Generation District Heating (4GDH) system as a coherent technological and institutional concept, which by means of smart thermal grids assists the

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\textsuperscript{2} SysML stands for System Modeling Language. It is a tool used in Model Based Systems Engineering in order to describe/communicate/clarify how a system is composed and how it behaves along with the requirements that it ought to satisfy.


\textsuperscript{4} http://www.4dh.eu
appropriate development of sustainable energy systems. In both these examples, the major enabler of their development are CPSs.

But one thing is often missing: what is the underlying communication structure that enables this vision. When it comes to 4GDH, it is clear that making use of renewable energies, such as the wind, requires quick, authenticated and authorized information to be communicated between the different stakeholders and systems. This inter-system communication is essential between all the cooperative systems. But will all these systems have the same type of communications? Certainly not! Without approaching the discussion on proprietary protocols, one can refer to the development of technology, e.g., 20 years ago WiFi and Bluetooth were not a common reality.

The major point with the above paragraphs is that the vision includes a collection of somewhat undefined systems that must cooperate with each other. The vision reflects the conceptualization of the 4th Generation of District Heating and incorporates the ideas of OPTi, which include OPTi-Sim. The consequence of that point is that within OPTi, there is a need to present a potential and feasible solution that empowers this cooperation in the present and consider the future. The proposed solution is a Service Oriented Architecture (SOA).

7.2 **SERVICE ORIENTED ARCHITECTURE**

SOA is a concept where software components offer services to the other components through a communication protocol over a network. Some of these components are service providers while others are service consumers. Naturally they can be both: providers and consumers.

SOA is of interest as it can address the reality where systems are operating in dynamic and changeable real-time environments. The application components do not have to be fixed at design time, can evolve with time and can begin to interact at runtime. This is usually referred to components that are loosely coupled and late binding. One implication of this is that SOA requires that service providers register their services at runtime.

SOA is not new. It is found in the World Wide Web and Internet of Things (IoT). To make things more tangible, one can consider the common example of Internet banking. A user, via his web browser, wants to know his account balance at his bank. The user is the service consumer and the bank server is the service provider. The user, not knowing the IP address of the bank server, types the URI of his bank in his browser, which is then transparently passed on to a DNS (Domain Name System) server to obtain the IP address. The user is then asked to authenticate himself before the service is provided. When considering IoT, the service provider could be a simple light bulb, which has its own IP address, within a house.

Having stated the above, the idea of SOA needs to be projected onto an industrial setting within a structure that supports the future, or in other words: a framework.
7.3 The Arrowhead Framework

The Arrowhead Framework is an open source SOA framework (Jerker Delsing, 2017), (J Delsing, 2016). It is the product of the large ARTEMIS Joint Undertaking project Arrowhead\(^5\). The project’s vision has been to enable collaborative automation by networked embedded devices. Its grand challenges were to enable the interoperability and integrability of services provided by almost any device. This has been done by offering services established on the Internet Protocol Suite, which is a proven technology. The different software modules that are the service providers and consumers can be updated at any time without affecting the other as they are loosely coupled and late binding. What is clearly defined are the interface themselves. Adhering to the international standards simplifies development and insures quality.

To maintain low latency in control loops and increase security, the Arrowhead Framework proposes the idea of local cloud. Within such a local cloud, one finds an assortment of services, in the form of software modules, of which three are core services. The mandatory three core services are the Service Registry, Authorization and Orchestration. Of the many other support service modules, worth mentioning are the Historian, the Gate Keeper, the Quality of Service Manager, and the Translator. The Historian is a database that can log events and signals, the Gate Keeper is the one service through which one goes in and out of the local cloud. The Translator is a service provider that intervenes transparently when different component suppliers have chosen different Internet protocols, which could hinder collaboration due to dialects (Derhamy, 2016). The QoS manager tries to keep an eye on the running services to monitor the quality of service.

7.4 The Local Cloud

The concept of clouds on the Internet is nowadays well established. It is an information interaction with a server somewhere on the globe. When it comes to controlling some process, a few warning flags should pop up. One is latency or delay in the control loop. Communicating with a faraway server on a potentially congested network to obtain information or an actuation of a nearby device does not make sense. There is also a security issue. We could also point to the fact that large systems become complex, requiring extensive modelling and analysis to develop and maintain. To address these issues, the Arrowhead Framework introduces the idea of the local cloud. The local cloud is a self-contained and self-sufficient environment where services are advertised and registered and service consumers are guided to the most appropriate providers.

7.5 The Mandatory Core Services

Each cloud has its own set of core services necessary for the bare minimum SOA environment. This bare minimum has been set for very constrained systems. A collection of support services does exist and some are described in the next section.

The core services are the Service Registry, the Authorization service and the Orchestration service. The Service Registry keeps track of all available services at all times. The Orchestration service provides the address of the most suitable services to a service consumer’s request. The Authorization service ensures that the consumption of a service is authorized.

\(^5\) [http://www.arrowhead.eu](http://www.arrowhead.eu)
Another reason that these services are referred to as core services is that they depend on each other as they interact with each other. For example, the Orchestration needs to check with the Service Registry to find out which are the actual service available and with the Authorization Service if the consumption of a service is allowed prior to suggesting it to the service consumer.

When moving to more powerful processors, one finds quickly a need for additional support services.

7.6 The Support Services

The Arrowhead Framework offers a collection of support services, which are well described in the wiki, book and publications.

The Translator is a service that enables interoperability in a transparent manner. When a service provider registers its services, it includes details about the service, e.g., IP address, port, service name, units and protocol among other details. When the Orchestration finds the most suitable service provider but with some mismatch, e.g., protocol, it returns an address to service that belongs to the Translator. The Translator then intervenes in all communication between the service provider and consumer without either of them being aware of the issue.

The Historian is a database service that keeps track of information, e.g., signals. It can be queried and provides desired information in different formats to match the needs of the service consumer. Access to information from the Historian must be authorized to insure information security.

The Quality of Service Manager is a service that keeps track of the quality of services and can flag undesirable or unacceptable behaviours.

The Gate Keeper is the service one must go through to interact with the world outside the local cloud. It therefore offers a security towards any threat from outside the local cloud. Inter cloud communication empowers the solution to form Systems of Systems.

7.7 The Documentation and Migration towards SOA

Migrating towards a Service Oriented Architecture requires some planning. It is for this reason that using an existing framework facilitates the migration. Due to its sheer size, the Arrowhead project had a substantial dissemination plan, which resulted, among others, in scientific publications, a wiki and a book (Jerker Delsing, 2017), (J Delsing, 2016). Looking into the book and the wiki, one can find further procedure and templates that guides a system architect to document and build a system within this architecture and framework. We find a structure from System of systems to Systems onto Services.

7.8 SOA in OPTi

OPTi’s overarching goal is to create business benefit for the industry as well as to ensure optimal end-consumer satisfaction. This can only be achieved is by having all the parts work with each other to overcome the daily demand peak and accentuated by weather shift. This harmonious flow of information requires an architecture framework that promotes security, scalability, interoperability and a means to promote continuous development of the systems and thereby systems of systems. The Arrowhead Framework is able to do that.

OPTi’s challenges are large and is working hard towards its goal. To make progress and minimize overall delay risks, the work has been distributed. For example, OPTi-Sim shows a structure of SOA with its different modules communicating with each other. It is a collection of software modules that exchange information using the clear interface, Functional Mockup Interface (FMI). It is however not following a SOA since it does
not advertise its service. In other words, its functionality is fixed at design time rather than at runtime. This could be changed later on once the simulation tool is validated and the benefit of SOA in the simulation is communicated through demonstration. What could be the benefits of SOA in simulation and in the goal of OPTi? To understand how to best make use of thermal energy, how to temporarily store it as weather changes along with demand, one needs to simulate the near future, such that demand responds automatically to production and distribution capabilities. As we approach the 4GDH, the stakeholders (e.g., suppliers) are different and increasing in numbers. Having a centralized simulation environment will become too heavy. Instead we could distribute the simulation to each stakeholder for its own purpose. A thermal energy supplier or consumer can simulate its own need and offer that as a service. But creating this scenario now implies a dependence; an additional risk within the project. Instead SOA is evaluated by itself within OPTi in a small thermal energy context: “how would SOA, using the Arrowhead Framework, would be built and function in a single-family home substation?” We therefore work to present how a local cloud would be built within a substation (cf., right most block in first Figure 24). This includes describing clearly how service registry and orchestration along with authentication (security) interact. The work is to include interoperability between components, e.g., from different manufacturers that use different communication protocols. The research includes component failure and reconfiguration at runtime. Stated differently, SOA in DHC must be demonstrated to be functional, secure, adaptable and scalable.

![Figure 25: District heating substation diagram with "S" as wireless web servers.](image)

### 7.9 A SUBSTATION LOCAL CLOUD

To demonstrate the concept of SOA in DHC, we make use of an earlier modified single house family substation (see Figure 25). The heat meter, the temperature sensors, valve control and circulation pump are all web servers (“S”’s in Figure 25) (Gustafsson, Delsing, & Deventer, 2010; van Deventer et al., 2010). The wireless nodes and gateway for OPTi are shown Figure 30.

The servers connect to the Internet via an access point. This substation form a local cloud and has the three core services: service registration, orchestration and authorization. In this specific case, they reside on the access point. Figure 26 shows the block diagram of the access point.
The DH application is a service consumer that needs services from the outdoor and radiator return temperature sensors as well as the control valve to regulate the temperature toward the radiator.

Figure 27 shows a sequence diagram of how the registration, the orchestration and the authorization take place. The advertising or posting of the service to the Service Registry is with a message that looks like Figure 28. The reply to a request temperature to that service is shown in Figure 29. This work was presented and published at the 15th International Symposium on District Heating and Cooling in September 2016.

Figure 26: bdd of a gateway with hardware and software modules.

Figure 27: Sequence diagram of temperature service registry and consumption.

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6 http://www.dhc2016.kr/
The ongoing research points to interoperability and reconfiguration. In the first case, the components might use a different communication protocol, because, e.g., they are from different manufacturers. The Arrowhead Framework provides a translator that is transparently invoked by the orchestrator since the protocol used is part of the message used in the service registry process. The other ongoing work has to do with reconfiguration of the system when a service fails. The example chosen here is the failure of the outdoor sensor. When it is detected, the orchestration service must provide an alternate source information, thus reconfiguring the system at runtime.

```json
{
"name": "temperature-em219",
"type": "temp-json-coap_udp",
"host": "[fdff:df5:8c6a:5ca2:44a6]",
"port": 5683,
"properties": {
"property": [
{
"name": "version",
"value": "1.0"
},
{
"name": "path",
"value": "/temperature"
}
]
}
}
```

**Figure 28:** Temperature service message to the Registry Service.

```json
{  
  "e": {
    "n":"urn:dev:mac:0024bffee804ff1",
    "t":1425256855,
    "u":"Celsius",
    "v":23.5
  }
}
```

**Figure 29:** Temperature service message to the consumer application.

There is an exciting by-product of this mechanism. Another service of the support services of the framework is the Quality of Service Manager, which can then detect if a sensor’s reading is not correct although not offline. Further failures can, in similar fashion, be flagged for, e.g. a perforated heat exchanger. Such diagnostics are possible when simulating the substation and building in question. This concept ties the idea back to OPTi-Sim in particular and OPTi in general.

The OPTi Framework can easily adopt a Service Oriented Architecture. To minimize risks and increase quality and impact, concepts have been separated and ran in parallel. OPTi-Sim is developed on one side and SOA is being demonstrated in a small scale setting to really convince of its benefit to DHC.
**Figure 30:** Collection of tiny web servers (upper left), temperature and interface nodes (lower left), and gateway (silver box) with its content above.
8 CONCLUSIONS

The developed tools and the used structures and architectures within the context of WP5 are described in this deliverable. It is clear that the developed tools can bring more insights and improvements about the operation of the DHC plants and can improve the performance.

The control configuration selection will provide the optimum selection of the paring and will provide a better understanding about the influence of different action on different part of the network. Also, it can help to provide a better understanding about some existing behaviour like, oscillation or plant wide disturbances.

The Automatic synthesis tool will provide an improvement in the performance of the building substations. The tool will increase the efficiency of these station by achieving a better behaviour of the controller and to diagnose the performance of the substations. The optimization based control will provide a closed loop control that will enable the optimization of different stages of the network.

The service oriented architecture will help the integration of different components of the system, better exchange of information and a reliable control structure. This will make the overall system robust and resilient for any changes and absence of some measurements and control devices.

Finally, the application, testing and validation of the presented tools and concepts are conducted under work packages 5 and 6 and will be presented in detail in the upcoming deliverables.
REFERENCES


Gustafsson, J., Delsing, J., & Deventer, J. Van. (2010). INTEGRATION OF AN IP BASED LOW-POWER SENSOR NETWORK IN DISTRICT HEATING SUBSTATIONS.


### List of Abbreviations

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<th>Abbreviation</th>
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<tr>
<td>(A)DR</td>
<td>(Automated) demand response</td>
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<td>bdd</td>
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<tr>
<td>DHC</td>
<td>District heating and cooling</td>
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<tr>
<td>FMI</td>
<td>Functional Mock-up Interface</td>
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<tr>
<td>FMU</td>
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<tr>
<td>GUI</td>
<td>Graphical user interface</td>
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<tr>
<td>LLC</td>
<td>Low level control</td>
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<tr>
<td>MPC</td>
<td>Model predictive control</td>
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<td>PID</td>
<td>Proportional-integral-derivative controller</td>
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